IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

A MICROPROCESSOR-BASED FEEDBACK SYSTEM FOR PHASE AND AMPLITUDE STABILIZATION OF SUPERCONDUCTING RESONATORS*

J. R. Delayen, G. J. Dick and J. E. Mercereau
California Institute of Technology
Low Temperature Physics 63-37
Pasadena, California 91125

ABSTRACT

A microprocessor-based feedback system has been designed, built and tested to provide phase and amplitude stabilization of a 150 MHz superconducting split-ring accelerating resonator for heavy ions. This system has a bandwidth of 400 kHz and can operate with positive feedback as a limiter or with negative feedback locking to an external reference. Direct negative feedback has already been used to stabilize the phase of a split-loop resonator to an accuracy of 0.01 radian at 2 MV/m.[1] All of the parameters of the system: gains, phase shifts, level reference, phase reference and frequency of the synthesizer are digitally controlled either manually or by the microprocessor. The advantages of this control system include automatic operation of the accelerator, pre-warning of an eventual breakdown of a resonator, and automatic recovery from such a breakdown.

INTRODUCTION

This paper describes a microprocessor-based feedback system for stabilizing the phase and amplitude of the electromagnetic field contained in a superconducting resonator. It also presents the results of stabilization tests performed on a 150 MHz split-ring resonator. The system was designed to fulfill several requirements. Firstly, it had to be flexible enough so that any control function deemed necessary could be implemented easily; secondly, there should be easy access to all the parameters of the system either manually or automatically; and thirdly, it was designed not only as a stabilizing system for a single resonator but also as a building block in the stabilization system for a full scale, many resonator, heavy-ion accelerator.

DESCRIPTION

The total RF power P_t required to stabilize a resonator electronically, at a given energy content U, is composed to two parts: P_a, the real power which energizes the cavity and P_r, the reactive power necessary to compensate for frequency deviations $\delta\omega$. Those two powers are functions of Q_L, the loaded Q of the resonator. While P_a increases with decreasing Q_L (beyond critical coupling), P_r decreases and there is an optional coupling which minimizes the total power P_t. When the intrinsic bandwidth $\Delta\omega_o$ of the resonator is much smaller than the maximum frequency deviation $\delta\omega_{max}$, this occurs at $\Delta\omega_L = 2\delta\omega_{max}$, where $\Delta\omega_L$ is the loaded bandwidth. The total power which is then required to counteract a frequency deviation $\delta\omega_{max}$ at energy content U is $P_t = U\delta\omega_{max}$.

The split-ring resonator has the feature that both $\delta\omega_{max}$ and U at the operating field are sufficiently small[2] that a simple direct negative feedback system without external voltage controlled reactance[5] is sufficient to provide amplitude and phase stability.

Drive Loop

In this system shown in Fig. 1, the controlled element is a self-excited feedback loop containing the

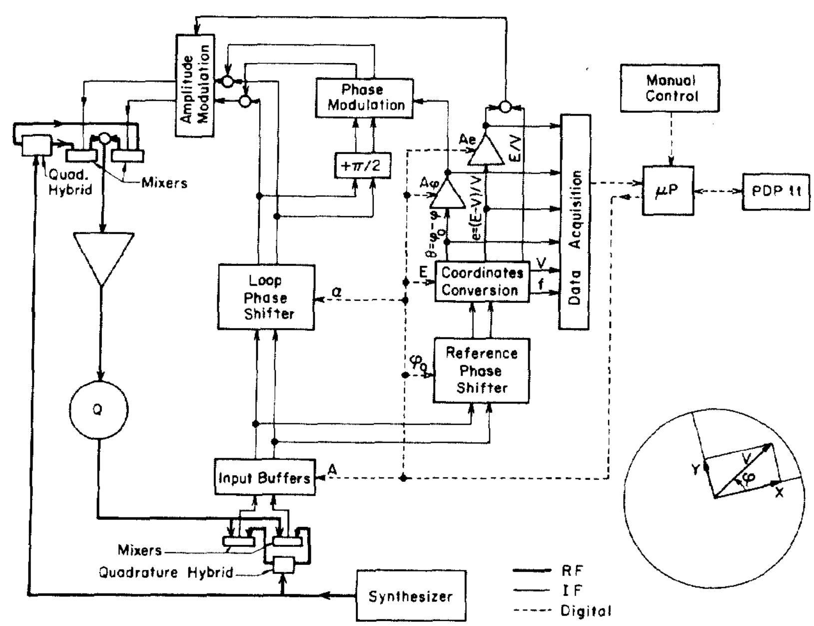

Fig. 1. Block diagram of the stabilization system for a single resonator.

*Work supported NSF Grant No. PHY76-20406 resonator and not simply a generator driven resonator. This has the advantage that even in an unlocked condition the loop still oscillates and the resonator fields are stable. Also a self excited loop does not have ponderomotive instabilities which are common in generator driven resonators.

In order to provide the design flexibility mentioned in the introduction, the system is controlled at audio frequency (IF) where signals are more easily manipulated than at the 150 MHz frequency (RF) of the resonator. The first element of this system is therefore an RF-IF interface shown in Fig. 1. A reference signal provided by a frequency synthesizer is split in two 90^{o} out of phase signals by a quadrature hybrid, and each of these is mixed with the resonator output. The low frequency components of these mixed signals provide two IF signals X and Y which are the components of the cavity signal in the rotating frame of the reference. After processing, these two IF signals are used to modulate the original two reference signals from the synthesizer; the outputs are then added to recover the original frequency and drive the resonator via a power amplifier.

The self-excited drive loop is completed in the IF section of the system with digitally controlled input buffers and phase shifter, and a modulation stage. The phase shifter is built around 4 multiplying digital to analog converters and provides 2 outputs which are linear combinations of the 2 inputs, the coefficients are the cosine and the sine of the shifting angle and are set digitally. This phase shifter is used to provide a total loop phase shift of a multiple of 2π. The rectangular to polar coordinates conversion module generates from its inputs: $V = \sqrt{X^2+Y^2}$ amplitude of the input signal, $\theta = \varphi_o - \varphi$ phase error which is used in the control loop where φ_o is the reference phase and $\varphi = \mathrm{Arctan}(X/Y)$ is the input phase, f instantaneous frequency difference between the self-excited loop and the frequency reference, E/V and $e = (E-V)/V$ where E is a digitally set amplitude reference. E/V is used to modulate the outputs of the loop phase shifter. The RF signal driving the resonator thus is of constant amplitude and may be phase shifted by a constant amount. In the unlocked state, this part of the system operates as a limiter and phase shifter in a self-excited loop.

Control Loop

Locking of this self-excited drive loop is accomplished by control of the phase and amplitude of the loop oscillations with respect to a reference (see Fig. 1). To provide locking of the amplitude V to the reference amplitude E, the amplitude error $e = (E-V)/V$ is used for control purposes after being amplified by a programmable gain amplifier. Phase locking is accomplished by adding a signal in quadrature with the loop signal whose amplitude is proportional to the phase error θ between the self-excited loop and the synthesizer. A second phase shifter of angle $-\varphi_o$ placed before the coordinates conversion allows locking to the phase reference within an arbitrary digitally set phase difference.

All the parameters of the system are digitally controlled by the microprocessor; these include: A (input buffers gain), α(loop phase shift), φ_o(phase reference), E(Amplitude reference), A_e(amplitude feedback gain), A_φ(phase feedback gain). A data acquisition module provides information to the microprocessor about the behavior and performance of the system. The bandwidth of the IF section of this feedback system was designed to be at least 400 kHz, so it will remain stable even under high feedback gain. Since it operates at audio frequency it can be used to stabilize resonators of any frequency without modification. The RF-IF interface was designed to operate between 125 and 250 MHz; replacement of the quadrature hybrids would be sufficient to extend the working range toward lower or higher frequencies.

The tuning range of this feedback system is limited by the amount of power available from the drive amplifier. As was mentioned earlier, in this application the power required is small enough so direct feedback is adequate. However, if necessary, this continuous tuning system could also be augmented by a PIN diode tuning system,[3] under the conditions of high frequency excursions or high energy content. It would then provide tuning within a discrete frequency band dictated by the PIN diodes. The switching between adjacent overlapping bands by the PIN diodes would be controlled by the microprocessor, and the switching rate would be of the order of the mechanical frequency of the resonator times the number of required bands.

EXPERIMENTS

This control system has been developed to stabilize resonators for use as accelerating structures for heavy ions. A series of experiments have been performed to test this system in conjunction with a 150 MHz lead (Pb) plated split-ring resonator at 4.2^{o}K. Figure 2 shows an experimental determination of the probability density of the instantaneous frequency of an unlocked resonator in the ambient laboratory environment. These

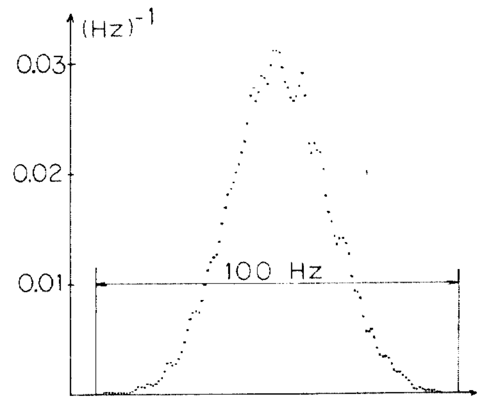

Fig. 2. Probability density of the resonant frequency of a 150 MHz superconducting split-ring resonator.

results were obtained by the microprocessor performing 10,000 measurements in 40 sec of (f) the difference between the loop frequency which tracks the resonator frequency, and the reference synthesizer frequency. This typical peak to peak excursion of 100 Hz in the resonant frequency (~150MHz) is much larger than the intrinsic bandwidth of the resonator (~20Hz) and is due to ambient mechanical vibrations. The only mechanical mode of the resonator which couples efficiently to the electromagnetic field is a torsional mode of the split-ring where the two drift tubes move in opposite direction along the beam line and has a frequency of 47 Hz. Figure 2 shows the typical Gaussian distribution of an oscillator excited by noise.

Figure 3 shows the residual amplitude and phase noise in the resonator fields when the resonator was locked to the synthesizer at an accelerating field of 1.8 MV/m. This accelerating field was set by the amount of RF power available and not limited by the capability of the feedback system. Stabilization of 150 MHz split rings by this technique should be possible up to fields of 3 MV/m with 200w of RF power and 200 Hz_{p-p} of ambient vibrations. In this demonstration, the phase was controlled to $<\pm\ 0.1^{o}$ and the amplitude to $<\pm\ 0.1\%$. The characteristic frequency of the noise is that of the

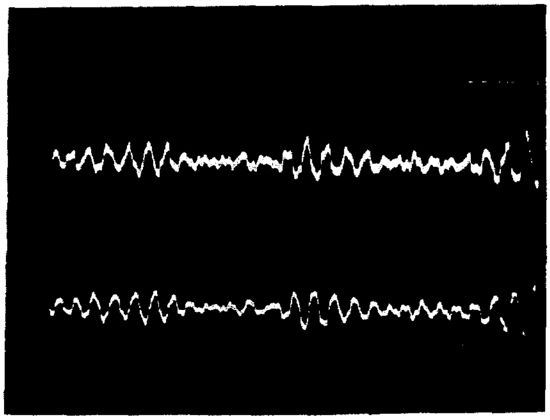

Fig. 3. Residual phase and amplitude noise at 1.8 MV/m
Top trace: amplitude noise: 0.2%/division.
Bottom trace: phase noise: 0.2°/division.
Horizontal: 50 ms/division.

mechanical mode, and the coupling between the phase and amplitude feedback resulted from operating with the resonator frequency different from the loop frequency.

During one test, ponderomovtive instabilities were observed. They were produced electronically by a narrow band RF power amplifier operating on one flank introducing a frequency-dependent limiter and phase shifter in the self-excited loop. However, these instabilities were easily removed in the unlocked and locked state by microprocessor control by observing the rate of change of the resonant frequency and introducing a small amount of modulation(< 1%) of the reference amplitude E with the right time delay. The value of the resonant frequency can be obtained in the unlocked state from f, difference between the loop frequency and the synthesizer frequency and in the locked state from $A_{\varphi}\theta$ which is the amount of additional phase shift which has to be introduced in the self-excited loop to provide frequency locking and is proportional to the frequency difference. In addition to controlling the feedback system, the microprocessor has been designed to simultaneously monitor the flow of information between a remote control manual input, the feedback system, a teletype, a line printer and a PDP computer.

CONTROL SYSTEM FOR A HEAVY ION SUPERCONDUCTING ACCELERATOR

A complete control system for a full scale superconducting heavy ion accelerator[4] is currently under study. A schematic of this system is shown in Fig. 4. Each resonator will have its own feedback system including an RF-IF interface, an IF-digital interface, a microprocessor and a slow mechanical tuning system to adjust the average frequency of each resonator to that of the frequency reference. All the microprocessors will be linked to an PDP 11-34 minicomputer through an HP interface bus (IEEE Standard 488) along with controls for the bunchers, the quadrupole power supplies, the frequency reference and various data acquisition systems.

The capability of adjusting the amplitude and the phase of the field in each resonator provides the operator with flexibility in tailoring the acceleration and phase profile along the beam to each energy gain and particle mass, thus providing a wide useful mass range while preserving the quality of the beam.

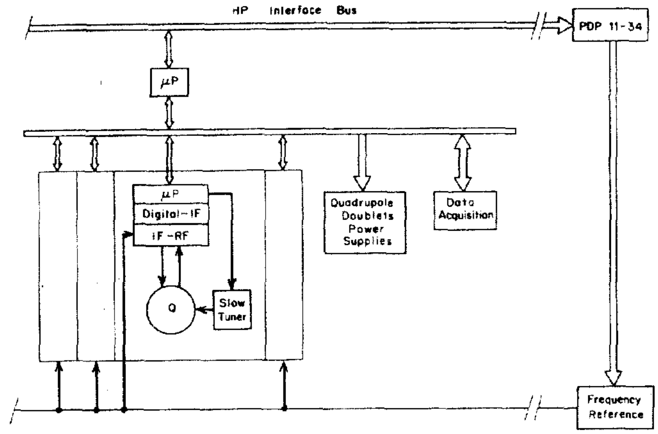

Fig. 4. Block diagram of the stabilization system of one module. The accelerator will be composed of 4 modules of 4 low β resonators, 6 modules of 3 high β resonators, and 2 bunchers which will be identical to the accelerating resonators and will have the same stabilization system.

The bus-oriented structure of this system provides a two way communication between the minicomputer and the microprocessors: the minicomputer informing each microprocessor about what its feedback parameters should be, the microprocessor giving a few milliseconds prewarning to the minicomputer of an eventual loss of lock of a resonator, which in turn can shut-off the beam, and turn it on again when lock was recovered.

CONCLUSION

A microprocessor-controlled feedback system for superconducting accelerating resonators has been designed, built and tested. Experimental results show that it is adequate to stabilize split-ring resonators in both phase and amplitude at field levels appropriate for acceleration purposes. Based on this system an accelerator control system can be implemented which has both great capability and flexibility.

REFERENCES

1. G. J. Dick, T. Yogi, J. R. Delayen, J. E. Mercereau, G. D. Sprouse and T. M. Cormier. Nucl Instr. Mtds. 138, 203 (1976).

2. K. W. Shepard, J. E. Mercereau and G. J. Dick, IEEE Trans. Nucl. Sci. NS-22, 1179 (1975).

3. G. J. Dick and K. W. Shepard, Proc. 1972 Applied Superconductivity Conf., IEEE Pub. No 72 CHO 682-5-TABSC. pp. 649-652 (1972).

4. J. W. Noe, P. Paul, G. D. Sprouse, G. J. Dick and J. E. Mercereau, 1977 Particle Accelerator Conf., to be published.

5. O. D. Despe, K. W. Johnson and T. K. Khoe, IEEE Trans. Nucl. Sci. NS-20, 71 (1973).